

## **FINAL TECHNICAL REPORT**

(12/12/2005)

**Project Title:** Error Covariance Estimation and Representation for Mesoscale Data Assimilation

ONR Award No.: N000140310822

Period: 5/15/2003 - 9/30/2005

**Principal investigator:** Qin Xu

### **Long-term Goals**

Explore and develop new ideas and methods for error covariance estimation and representation to improve mesoscale data assimilation and numerical weather prediction.

### **Objectives**

Explore and develop new ways to study and estimate observation and background error covariances, especially the non-homogenous, non-isotropic and/or flow-dependent aspects of background error covariances. Explore new and efficient representations of the inverse covariances in the variational formulations for mesoscale data assimilation.

### **Approaches**

Built upon the existing spectral correlation model in the innovation method, a new spline-spectral covariance model can be developed to estimate not only the background error correlation function but also the spatial variations of background error variance. The new method can be applied to innovation (observation minus forecast) data collected from Navy's numerical weather prediction (NWP) systems.

The innovation method can be reformulated with a non-isotropic correlation model for high-resolution radar velocity innovation data. The reformulated method can estimate not only the mesoscale background error covariance but also the radar radial-velocity observation error variance and correlation between neighboring range gates and beams.

By using the proposed functional approach and generalized Fourier transformation, advanced mathematical formalisms can be developed to represent the inverse of the background error covariance by a differential operator, called D-operator. The D-operator can be used to improve the 3.5-dimensional variational (3.5dVar) radar data assimilation technique developed for the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)

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## Major research activities and accomplishments

1. The spectral correlation model was extended into a new spline-spectral covariance model to refine the innovation method for error covariance estimation. The refined method can estimate the horizontal variation of the background error variance in addition to the background error correlation function. The refined method was applied to innovation data collected from the new Navy's Variational Data Assimilation System (NAVDAS). The estimated errors were compared with those obtained from the old Multivariate Optimum Interpolation (MVOI). The results revealed that the background errors were reduced by the new NAVDAS in comparison with the old MVOI (see the example in Fig. 1 of MMxu04a.doc in the FY04 progress report). The estimated error statistics provide useful information for future improvements of NAVDAS data assimilation.

2. A non-isotropic form of cross-covariance function between the radial component and tangential component (with respect to the radar beam direction) of background wind errors was derived. This cross-covariance function was used together with the auto-covariance function derived for the radial component to construct the background error covariance matrix and to analyze the vector wind field from Doppler radial-wind observations on the conical surface of radar scans. The utilities of these covariance functions for vector wind analyses were demonstrated by numerical experiments (Xu et al. 2005b).

The non-isotropic form of error correlation function for radial winds was used to reformulate the innovation method to estimate mesoscale error covariances from high-resolution radar radial-velocity innovation (observation minus forecast background) data. The reformulated method provided the first objective way with a statistical tool for radar velocity observation error covariance estimation. By relaxing the conventionally assumed non-correlation between observation errors, the method was shown to be able to estimate not only radar observation error variance but also observation error correlation between neighboring gates or beams of radar scans at very fine scales (see the example in Fig. 2 of MMxu05a.doc in the FY05 progress report).

The reformulated method was extended (from single) to multiple radars, so mesoscale background wind error covariance can be estimated from high-resolution wind innovation data from a network of radars. Data grouping strategies were designed to improve the computational efficiency of the method and to enhance its capability and accuracy in detecting radar data quality problems and estimating radar wind observation error to very high resolutions. The method was applied to radar observations collected by the Oklahoma City airport terminal Doppler weather radar (TDWR) and by the NSSL Dual-Polarization KOUN radar (Xu et al. 2003, 2005c). The method was also applied to the NSSL phased array radar observations collected for a squall line case (Xu et al. 2005a). With the fast phased array radar scans, radial-velocity innovation data can be accumulated rapidly and used nearly real time to estimate the radar observation error and background error covariances. The 3.5dVar radar data assimilation package was upgraded to use the estimated error covariances. This led to an integrated approach in phased array radar data assimilation (Xu et al. 2005a).

3. In the cost-function of three- or four-dimensional variational data assimilation, each term is weighted by the inverse of its associated error covariance matrix and the background error covariance matrix is usually much larger than other covariance matrices. Although the background error covariances are traditionally parameterized by simple smooth correlation functions, the covariance matrices constructed from these correlation functions are often too large to be inverted. By using the proposed functional approach, the background error covariance was formulated by an integral operator in the continuous limit. The inverse covariance was then derived, as an inverse operator, by using the generalized Fourier transformation. The derived inverse yielded a direct representation of the inverse covariance in the form of vector differential operator, called D-operator. This allows the background term to be formulated by the  $L_2$  norm of a D-operator applied to the field of analysis increment, so the effect of the inverse error covariance matrix can be represented directly by a D-operator without inverting the matrix. The D-operator formulation was also extended to multivariate covariances (Xu 2005). Efficient algorithms were developed to construct D-operators for practical applications.

Numerical experiments were performed to compare the D-operator with the recursive filter. Each was further combined with a finite-element B-spline representation to reduce the dimension of control variable space and improve the computational efficiency. In combination with the B-spline representation, the D-operator was found to be more efficient than the recursive filter, but the recursive filter could improve the preconditioning for the minimization. Certain relationships between multivariate error variances and between multivariate error decorrelation lengths were derived and coded with the D-operator and recursive filter (in two different options) into the upgraded 3.5dVar radar data assimilation package. The upgraded 3.5dVar radar data assimilation package was delivered to NRL Monterey for nowcast applications and COAMPS radar data assimilation (Zhao et al. 2005).

## Publications

- Gong, J., L. Wang, and Q. Xu, 2003: A three-step dealiasing method for Doppler velocity data quality control. *J. Atmos. & Oceanic Technology*, **20**, 1738-1748.
- Liu, S., Q. Xu, and P. Zhang, 2005: Quality control of Doppler velocities contaminated by migrating birds. Part II: Bayes identification and probability tests. *J. Atmos. Oceanic Technol.* **22**, 1114-1121.
- Liu, S., P. Zhang, L. Wang, J. Gong, and Q. Xu, 2003: Problems and solutions in real-time Doppler wind retrievals. Preprints, *31th Conference on Radar Meteorology*, 6-12 August 2003, Seattle, Washington, Amer. Meteor. Soc., 308-309.
- Xu, Q., 2005: Representations of inverse covariances by differential operators. *Adv. Atmos. Sci.*, **22**, 181-198.
- Xu, Q., L. Wang, and K. Nai, 2003: Error covariance estimation for Doppler wind data assimilation. Preprints, *31th Conference on Radar Meteorology*, 6-12 August 2003, Seattle, Washington, Amer. Meteor. Soc., 108-109.
- Xu, Q., L. Wang, P. Zhang, S. Liu, Q. Zhao, K. Sashegyi, and J. Nachamkin, 2004: Progress in radar data quality control and assimilation. *Sixth International Symposium of*

- Hydrological Applications of Weather Radar*, 2-4 February 2004, Melbourne, Australia, Bureau of Meteorology & Australian Meteor. Oceanographic Soc., Conference CD.
- Xu, Q., K. Nai, L. Wei, P. Zhang, L. Wang, and H. Lu, Qingyun Zhao, 2005a: Progress in doppler radar data assimilation. *32nd Conference on Radar Meteorology*, 24-29 October 2005, Albuquerque, New Mexico, Amer. Meteor. Soc., JP1J7, Conference CD.
- Xu, Q., and B. Zhou, 2003: Retrieving soil moisture from soil temperature measurements by using linear regression. *Adv. Atmos. Sci.*, **20**, 849-858.
- Zhao, Q., J. Cook, Q. Xu, and P. Harasti 2005: Using radar wind observations to improve mesoscale numerical weather prediction. Accepted by *Wea. Forecasting*.
- Zhang, P., S. Liu, L. Bi, and Q. Xu, 2003: Real-time WSR-88D velocity data quality control on bird detection. Preprints, *31th Conference on Radar Meteorology*, 6-12 August 2003, Seattle, Washington, Amer. Meteor. Soc., 473-474.
- Zhang, P., S. Liu, and Q. Xu, 2005: Quality control of Doppler velocities contaminated by migrating birds. Part I: Feature extraction and quality control parameters. *J. Atmos. Oceanic Technol.*, **22**, 1105-1113.
- Zhang, P., S. Liu, Q. Xu, Lulin Song, 2005: Storm targeted radar wind retrieval system. *32nd Conference on Radar Meteorology*, 24-29 October 2005, Albuquerque, New Mexico, Amer. Meteor. Soc., P8R1, Conference CD.

#### Submissions

- Liu, S., M. Xue, and Q. Xu, 2005: Using wavelet analysis to detect tornadoes from Doppler radar radial-velocity observations. Submitted to *J. Atmos. Oceanic Technol.*
- Xu, Q., S. Liu and M. Xue, 2005b: Background error covariance functions for vector wind analysis using Doppler radar radial-velocity observations. Submitted to *Quart. J. Roy. Meteor. Soc.*
- Xu, Q., K. Nai, and L. Wei, 2005c: An innovation method for estimating radar radial-velocity observation error and background wind error covariances. Submitted to *Quart. J. Roy. Meteor. Soc.*

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 13-12-2005		2. REPORT TYPE Final Technical		3. DATES COVERED (From - To) 5/15/2003 - 9/30/2005		
4. TITLE AND SUBTITLE Error Covariance Estimation and Representation for Mesoscale Data Assimilation				5a. CONTRACT NUMBER NA		
				5b. GRANT NUMBER N00014-03-1-0822		
				5c. PROGRAM ELEMENT NUMBER NA		
6. AUTHOR(S) Xu, Qin				5d. PROJECT NUMBER NA		
				5e. TASK NUMBER NA		
				5f. WORK UNIT NUMBER NA		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Board of Regents of the University of Oklahoma/Office of Research Services 731 Elm Avenue, Room 134 Norman, OK 73019-2113				8. PERFORMING ORGANIZATION REPORT NUMBER NA		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ballston Centre Tower One 800 North Quincy Street Arlington, VA 22217-5660				10. SPONSOR/MONITOR'S ACRONYM(S) NA		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NA		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unrestricted						
13. SUPPLEMENTARY NOTES NA						
14. ABSTRACT <p>The goal of this project is to explore and develop new methods of error covariance estimation and representation that can improve mesoscale data assimilation and numerical weather prediction. To this end, three research objectives were fulfilled:</p> <p>(i) A spline-spectral covariance model was developed to enhanced the capability of the innovation method for error covariance estimation. (ii) Non-isotropic error correlation functions were derived for radar radial-wind analysis and used to reformulate the innovation method. The reformulated method provided the first objective way to statistically estimate not only radar observation error variance but also observation error correlation between neighboring gates or beams of radar scans at very fine scales. (iii) By using the advanced functional approach and generalized Fourier transformation, the inverse of a covariance function was shown to be representable by a vector differential operator, called D-operator. With D-operator representations, the inverses error covariance matrices can be formulated directly and efficiently in the cost-functions of variational data assimilation.</p>						
15. SUBJECT TERMS Numerical weather prediction and meteorological data assimilation.						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UU	18. NUMBER OF PAGES  4	19a. NAME OF RESPONSIBLE PERSON Jennie I. Parker, SPC OU/ORS	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (405) 325-6054	